

PRODUCTION OF LIGHT GOLDSSTONE PARTICLES ON PHOTON COLLIDERS

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Abstract

By realizing the project of intensive γ beams with large energy (necessary for Photon Colliders) an essential flux of light Goldstone particles (LGP - axions, arions, familons, majorons) can be generated. The probability of LGP production is calculated for different densities of laser photons in the conversion region (with absorption of one or several laser photons). The method for observation of LGP via its absorption in the matter is also presented.

1 Introduction

The existence of Light Goldstone Particles (LGP), usually pseudoscalar (axion, arion, majoron, familon), is very attractive in many theoretical schemes (for recent review see e.g. [1, 2]). Such particles are still elusive. So, the new method of their possible discovery looks attractive. In this respect, the program of construction of Photon Colliders based on future Linear Colliders provides new opportunity.

To describe this opportunity we remind necessary features of obtaining Photon Colliders. The intense photon beams for Photon Collider should be obtained by backscattering of electrons prepared for the Linear Collider on the intense laser light [3, 4, 5, 6]. It is expected to obtain here the conversion coefficient k (the ratio of obtained high energy photons to the number of initial electrons N_e) close to 1. The main features of conversion are described by quantity x which determined via initial electron beam energy E and laser photon energy ω_0 as

$$x = \frac{4E\omega_0}{m_e^2}. \quad (1)$$

The best quality of photon spectra is obtained at highest values of x , which are limited from above by a value about $x_0 = 2(1 + \sqrt{2}) \approx 4,8$. The conversion coefficient $k = N_\gamma \sigma_C / S$, where N_γ is the number of photons in the laser bunch, S - its cross section in the conversion point and σ_C is the standard cross section of Compton scattering at c.m. energy $W_0 = m_e \sqrt{x + 1}$.

From this it follows that the conversion region can be considered as $e\gamma_0$ collider (γ_0 is the laser photon) with huge luminosity \mathcal{L} but small c.m.s. energy W_0 :

$$\mathcal{L} = f \frac{N_e N_\gamma}{S} = f \frac{k N_e}{\sigma_C} \approx 10^{45} \div 10^{46} \text{ cm}^{-2} \text{ year}^{-1}, \quad W_0 = m_e \sqrt{x + 1} \approx 1.2 \text{ MeV}. \quad (2)$$

Here N_e is the number of electrons in bunch and f is the repetition rate.

Therefore, this conversion region presents unique place for the study of LGP production if its mass is less than $W_0 - m_e$. This opportunity was studied in Refs. [7, 8, 9, 10]. In this paper we discuss new potential given by effects of high laser photon density in the conversion region. This high density makes strongly probable the processes

$$e + n\gamma_0 = e + X. \quad (3)$$

with simultaneous absorption of $n > 1$ laser photon¹. Evidently, in such a process the permissible region of LGP mass is expanded to values $\sim m_e(\sqrt{nx + 1} - 1)$.

To this goal we discuss briefly modern status of different LGP (section 2). Next we describe the method to calculate probabilities of processes under interest in the field of intense laser light (section 3). Last we discuss the proposed registration method (section 4).

¹ In the second mechanism of production $n\gamma_0 + \gamma \rightarrow X$ (where γ is the high energy photon) the number of produced LGP's is essentially less than that discussed in the text the corresponding cross section contains additional factor m_X^2/m_e^2

2 Various LGP's. Modern status.

The Effective Lagrangian describing an interaction of any LGP X_i with electrons and photons has the form

$$\mathcal{L} = g_{iee} \bar{e} \gamma_5 e X_i + C_{i\gamma\gamma} \frac{\alpha}{m_e} X_i \tilde{F} F \quad (4)$$

2.1 The "invisible" axion

The axion is a light pseudogoldstone boson, proposed for the solution of the CP-violation problem in strong interactions [11, 12]. The existence of this standard axion is practically forbidden by modern data (see e.g [13]). However, the idea of natural explanation of CP symmetry is attractive, and the theory of the standard axion was modified to make its interaction with matter weaker and to make it lighter.

The axion model with two Higgs doublets is characterized by the scale of breaking of the $U(1)$ -symmetry $f_{pq} \approx 246$ GeV and the mass $m_a \geq 150$ KeV, connected by one parameter: the ratio of the vacuum expectation value (VEV) of Higgs doublets.

The addition of new Higgs multiplets breaks relation between m_a and standard f_{pq} value. It happens that $250 \text{ GeV} \leq f_{pq} \leq 10^{19} \text{ GeV}$, the mass m_a , just as the coupling with matter can become sufficiently smaller than in the basic theory [1]. For example, one can introduce the additional scalar field ($SU(2) \times U(1)$ singlet) with arbitrary large VEV. The obtained "invisible" axion X_a is known as Dine-Fischler-Srednicki-Zhitnitsky axion (DFSZ) [14, 15].

The couplings g_{aee} and $C_{a\gamma\gamma}$ in eq. (4) are given by:

$$g_{aee} = \frac{m_a m_e}{f_\pi m_\pi} \frac{1+z}{N\sqrt{z}} \cos^2 \beta \approx 2.1 \frac{m_a m_e}{f_\pi m_\pi} \cos^2 \beta, \quad (5)$$

$$C_{a\gamma\gamma} = \frac{m_a m_e}{8\pi f_\pi m_\pi} 2\sqrt{z} \approx 0.06 \frac{m_a m_e}{f_\pi m_\pi}, \quad (6)$$

where $f_\pi = 94$ MeV is the pion decay constant, $z = m_u/m_d = 0.568$ is the ratio of the quark masses, N is the number of generations, $\tan \beta$ is the ratio of the VEV's of two Higgs fields. Respectively, the mass of axion is given by

$$m_a = m_\pi \frac{f_\pi}{f_a \sin 2\beta} \frac{2N\sqrt{z}}{1+z} \approx 0.96 m_\pi \frac{N f_\pi}{f_a \sin 2\beta}. \quad (7)$$

Another form of "invisible" axion was proposed in Refs. [16, 17], now it is known as hadronic or Kim-Shifman-Vainstein-Zakharov axion (KSVZ). This axion does not interact with leptons at the tree level. Therefore, its couplings to leptons and photons are two orders less compared to DFSZ axion.

The archion model [18] contains the global symmetry $U(1)$, its spontaneous breaking results in Goldstone boson, which has both diagonal and nondiagonal flavor interaction with fermions. But unlike the axion the archion has no interaction with photons and it is like a hadronic axion with strongly suppressed lepton interaction.

Modern experimental limitation for electron-axion coupling gives $g_{aee} < 3 \cdot 10^{-8}$ [20] (In this review limitation for pseudovector coupling $G_{aee} = g_{aee}/(2m_e)$ is presented.)

The astrophysical constraints on the VEV, mass and coupling of "invisible" axion [19] are very restrictive:

$$10^9 \text{ GeV} < f_a < 10^{12} \text{ GeV} \Rightarrow 0.5 \cdot 10^{-12} < g_{aee} < 0.5 \cdot 10^{-9},$$

$$0.6 \cdot 10^{-5} \text{ eV} < m_a < 0.6 \cdot 10^{-2} \text{ eV}.$$

2.2 The Arion X_α

The arion is a neutral, strictly massless, stable pseudoscalar boson with even charge parity, interacting with fermions [1]. The interaction of arion with lepton is described by an Effective Lagrangian (4) with:

$$g_{\alpha ee} = \tan \beta \frac{m_e}{v}, \quad v = (G_F \sqrt{2})^{-1/2} = 246 \text{ GeV}. \quad (8)$$

Here X_α is the arion field, $\tan \beta$ is the ratio of different VEVs, modern estimations in Higgs boson physics are in favor of $\tan \beta = 1 \div 40$. However, the astrophysical data are in favor of very small $\tan \beta$ (which are not forbidden yet in the standard two doublet Higgs models). Weakly interacting with a matter the arions

can be emitted from stars. The arion emission leads to fast loss of energy from the stars. The demand of the condition by which the arion luminosity of the Sun should not exceed the photon luminosity leads to $\tan \beta < 10^{-3}$. A more strong constraint appears from the evolution of red giants is $\tan \beta < 10^{-6}$.

It gives weak coupling with leptons $g_{aee} < 2 \cdot 10^{-9} - 2 \cdot 10^{-6}$.

2.3 The Majoron X_M

A spontaneously broken global symmetry of lepton number will lead to massive Majorana neutrinos and a Nambu-Goldstone boson, named the majoron. This can be accomplished by extending the Standard Model with an additional gauge-single Higgs field [22], or $SU(2)$ -triplet Higgs multiplet [21]. The respective Goldstone bosons are the Chikashige-Mohapatra-Peccei (CMP) Majoron and the Gelmini-Roncadelli (GR) Majoron.

CMP model requires the addition of a gauge-singlet Higgs field and a right-handed heavy neutrino. The effective Majoron-electron interaction induced at one-loop level is given by

$$\mathcal{L} = \frac{G_F}{16\pi^2} m_e m_\nu \bar{e} \gamma_5 e X_M \quad (9)$$

From the current upper bound $m_{\nu_e} < 10\text{ eV}$ it is easily seen that the coupling of the CMP Majoron to matter is extremely small ($g_{Mee} < 10^{-17}$).

An $SU(2)$ -triplet Higgs multiplet is introduced in GR Majoron model. The wave function of the GR Majoron is primarily the phase field of the neutral component and has a small admixture of the Higgs doublet with the mixing angle $2v_T/v_D$ (v_T and v_D being the VEV's of the Higgs triplet and doublet, respectively). As a consequence, the GR Majoron has a tree-level coupling to electrons

$$\mathcal{L} = 2\sqrt{2} G_F v_T m_e \bar{e} \gamma_5 e X_M \quad (10)$$

The astrophysical constraint from the consideration of majoron emission rates of the neutron-star core is $v_T < 2\text{ KeV}$.

Thus, we have the following constraint on the coupling with an electron: $g_{Mee} < 3.4 \cdot 10^{-14}$.

2.4 The Familon X_F

The familon is the Goldstone boson associated with the spontaneous breaking of a global family symmetry (horizontal symmetry) between the generation of the quarks and leptons [23]. Since the breaking of the horizontal group can takes place at small distance $1/F$ only, the familon, similar to the invisible axion, interacts weakly with the matter and its mass should be small.

The Effective Lagrangian for the interaction of a familon with a lepton at low energy has form (4) with $g_{Fee} = 2m_e/F$.

The absence of decay $K^+ \rightarrow \pi^+ X_F$ results in limitation $g_{Fee} < 0.8 \cdot 10^{-14}$ ($F > 1.3 \cdot 10^{11}\text{ GeV}$) [20]. The astrophysical constraint here is less restrictive, it gives $g_{Fee} = 2m_e/F < 1.4 \cdot 10^{-13}$ ($F > 7 \cdot 10^9\text{ GeV}$).

3 The calculations of probability and the number of events.

We consider the laser wave with circular polarization (which is the best for conversion [3]). Its vector potential has form $A_\mu = a_{1\mu} \cos \varphi + a_{2\mu} \sin \varphi$, $\varphi = kx$, where k_μ is the momentum of laser photon, ($ka_1 = ka_2 = a_1 a_2 = 0$, $a_1^2 = a_2^2 = a^2$).

The matrix element of the LGP production by an electron in external field can be written in the form

$$M_{fi} = ig_{Xee} \int d^4x \bar{\Psi}_e(x) \gamma_5 \Psi_e \Phi(x), \quad (11)$$

where $\Psi_e(x)$ and $\bar{\Psi}_e(x)$ are the exact solution of the Dirac equation for an electron in the field of a circularly polarized wave:

$$\Psi_e(x) = \left(1 + \frac{ek\hat{A}}{2kp}\right) u_p \exp\left(ie\frac{a_1 p}{kp} \sin \varphi - ie\frac{a_2 p}{kp} \cos \varphi + iqx\right), \quad \phi_X = \frac{e^{-ip_X x}}{\sqrt{2\epsilon_X}}. \quad (12)$$

Here ϵ_X, p_X is the energy and the momentum of LGP, p and q are the momentum and "quasimomentum" of an electron

$$q_\mu = p_\mu + \xi^2 \frac{m_e^2}{2kp} k_\mu, \quad \xi^2 = \frac{e^2 a^2}{m_e^2}.$$

Note that

$$m_*^2 = q_\mu q_\mu = m_e^2(1 + \xi^2).$$

This difference from m_e^2 is essential to find the production threshold.

Using standard techniques (see [24, 25]), we calculated the probability of LGP production by a non-polarized electron

$$dW = \frac{g_{Xee}^2 m_e}{64\pi} \sum W_n \frac{du}{(1+u)^2} \quad (13)$$

$$W_n = \frac{1}{\sqrt{nx + 1 + \xi^2}} \left(-2\eta^2 J_n^2(z) + \xi^2 \frac{u^2}{1+u} [J_{n+1}^2(z) + J_{n-1}^2(z) - 2J_n^2(z)] \right),$$

where $J_n(z)$ is the Bessel function of n -th order, $u = (kp_a)/(kp')$, p' is the momentum of a scattering electron,

$$\eta = \frac{m_X}{m_e}, \quad z = \frac{2\xi}{x} \sqrt{nx + 1 + \xi^2} \sqrt{\frac{(u_+ - u)(u - u_-)}{(1+u_+)(1+u_-)}}, \quad u_- < u < u_+,$$

$$u_\pm = \frac{nx + \eta^2 \pm \sqrt{(\eta^2 - nx)^2 - 4\eta^2(1 + \xi^2)}}{2 + nx + 2\xi^2 - \eta^2 \mp \sqrt{(\eta^2 - nx)^2 - 4\eta^2(1 + \xi^2)}}.$$

In formula (13) the term with given n describes the LGP production by an electron via absorption from electromagnetic wave n of laser photons simultaneously (3), n_{th} is the minimal number of photons for the Goldstone production with the mass m_X

$$n_{th} = \frac{1}{x}(\eta^2 + 2\eta\sqrt{1 + \xi^2}) \quad (14)$$

Integrating the expression (13) we get the total probability of the LGP production (in this case the term "cross section" cannot be used):

$$\frac{g_{Xee}^2 m_e}{64\pi} f(x, \xi, \eta).$$

In Figure 1 the dependence of function $f(x, \xi, \eta)$ shown at some values ξ .

At $\xi^2 \ll 1$, expanding the Bessel function in series, we get from (13)

$$dW_n = \frac{g_{Xee}^2 m_e (\xi/x)^{2n}}{64\pi n! \sqrt{nx + 1 + \xi^2}} D \frac{du}{(1+u)^2} \quad (15)$$

$$D = -2\eta^2 ((1 + \xi^2)(u_+ - u)(u - u_-))^n + \frac{x^2 n^2 u^2}{1+u} ((1 + \xi^2)(u_+ - u)(u - u_-))^{n-1}$$

For $n = 1$, integrating (15) by u , we get the production cross-section calculated in Ref. [7]:

$$\sigma = \frac{1}{2} \frac{\alpha g_{Xee}^2}{m_e^2} \frac{1}{x} \left\{ \left(1 - 2 \frac{\eta^2}{x} + \frac{2\eta^2(\eta^2 - 2)}{x^2} \right) \ln \left(\frac{4(x+1)}{2 + x - \eta^2 + \sqrt{(x - \eta^2)^2 - 4\eta^2}} \right) \right. \\ \left. + \sqrt{(x - \eta^2)^2 - 4\eta^2} \left(1 - \frac{7}{2}\eta^2 + \frac{3}{2}x - 8\frac{\eta^2}{x} - 7\frac{\eta^2}{x^2} \right) \right\}$$

At $x = 5$ this cross-section is:

$$\sigma \approx g_{Xee}^2 \cdot 5.4 \cdot 10^{-24} \text{ cm}^2$$

Numerical estimations. Here we use the physical parameters of the laser conversion region which are chosen in accordance with the projects of Photon Colliders [4, 5, 6]. In the conversion scheme, it has been proposed to use a laser with photon energy $\omega_0 = 1.17$ eV. The length of conversion region characterized by a high density of laser photons is $l \sim 1.5$ nm, which value is close to the length of the electron bunch. The invariant mass of the $\gamma_0 e$ -system for the energy of electron $E_e = 250$ GeV is

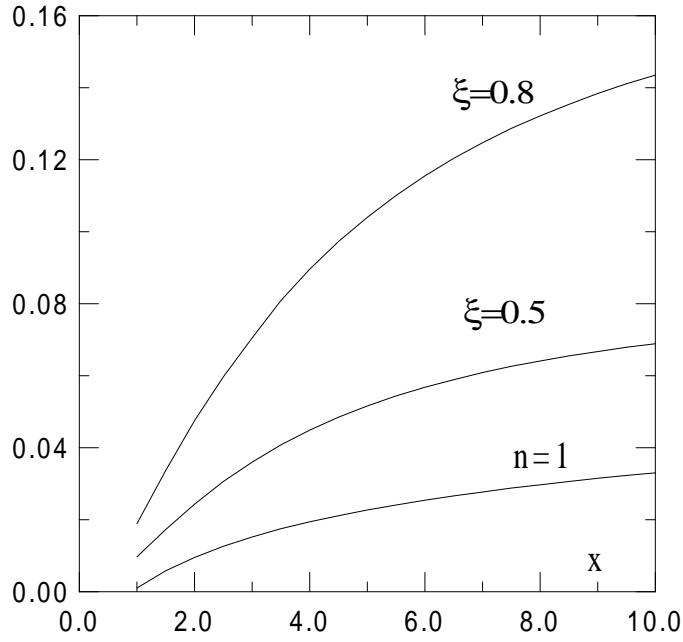


Figure 1: The dependence $f(x, \xi)$ on x at some values ξ and $\eta = 0$, curve $n=1$ corresponds to single photon absorption

comparable to the electron mass $W_0 \approx 1.21$ eV ($x = 4.5$). It is convenient to express ξ^2 in terms of the energy A , the duration τ and radius a_γ of the laser flash in the interaction point

$$\xi^2 = \frac{A}{A_*}, \quad \text{where} \quad A_* = \frac{\tau c}{4} \cdot \left(\frac{m_e \omega_0 a_\gamma c}{e \hbar} \right)^2.$$

For the values $\pi a_\gamma^2 \approx 10^{-5}$ cm² we have $A_* = 100$ J and at the energy of laser flash $A = 25$ J $\xi^2 = 0.25$. The value ξ^2 can reach 0.6. The number of produced LGP's is

$$N_X = \frac{N_e \tau}{2} \sum_{n > n_{th}} \int_{u_-}^{u_+} dW_n \quad (16)$$

The LGP energies are distributed in the interval

$$\frac{\eta^2}{(x + \eta^2)R} E_e < \epsilon_X < E_e \frac{x + \eta^2}{x + 1} R, \text{ where } R = \frac{1}{2} \left(1 + \sqrt{1 - \frac{4\eta^2(x + 1)}{(x + \eta^2)^2}} \right) \quad (17)$$

For $E_e = 250$ GeV at $m_X = 10$ KeV this corresponds to the interval

$$20 \text{ MeV} < \epsilon_X < 208 \text{ GeV}$$

. Since the effective mass of the $\gamma_0 e$ -system is not large the characteristic emission angles of Goldstones relative to the direction of the electron bunch are $\leq m_e/E_e \approx 10^{-5}$. Therefore the angular spread of Goldstones is defined by the angular spread of electrons in the beam ($\approx 10^{-4}$).

The numerical calculation of the number of LGP's and the used couplings are shown in the table. It is seen that a large number of axions or arions will generate from the discussed conversion.

Table

| | g_{Xee} | Cross-section $\sigma(cm^2)$ | The number of LGP per year |
|-------------------|----------------------|------------------------------|----------------------------|
| Standard axion | $2 \cdot 10^{-6}$ | $2.2 \cdot 10^{-35}$ | $7 \cdot 10^{10}$ |
| ”Invisible” axion | $3 \cdot 10^{-8}$ | $4.9 \cdot 10^{-39}$ | $1.5 \cdot 10^7$ |
| Arion | $2 \cdot 10^{-6}$ | $2 \cdot 10^{-35}$ | $7 \cdot 10^{10}$ |
| Familon | $1.4 \cdot 10^{-13}$ | $1 \cdot 10^{-49}$ | $3 \cdot 10^{-4}$ |
| Majoron | $3.4 \cdot 10^{-14}$ | $5 \cdot 10^{-51}$ | $1.5 \cdot 10^{-5}$ |

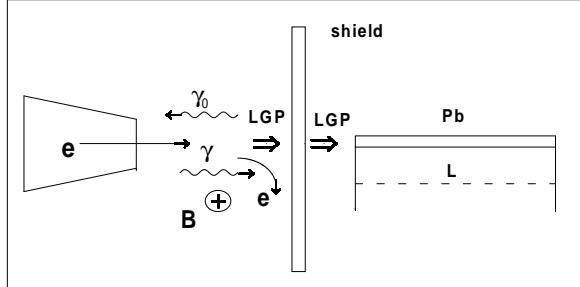


Figure 2: The scheme of LGP production and registration.

4 The registration

To see the obtained LGP the special simple detector is proposed. It should be some pin-type lead rod with radius about 2 cm and length about 100 m, placed in vacuum behind a shield to get rid of the background (Fig.2). The round scintillator with diameter in 1-3 m in the end of this device should detect particles produced in lead.

The LGP should interact with lead nuclei and production of hadrons:

$$X + Pb \rightarrow h \quad (\text{hadrons}) \quad (18)$$

This reaction will be observed as the production of hadron jets with total energy $\sim \epsilon_X$ and characteristic transverse momentum $p_\perp \sim 300 \text{ MeV}/c$. Let us evaluate the number of events for the case of standard axion. The cross-section of reaction (18) is $\sim A$ times as large as the cross-section of the axion–nucleon interaction, σ_{an} , where A is the number of nucleons in a nucleus. The cross-section $\sigma_{an} \approx f_{a\pi} \sigma_{\pi n} (v/f_{pq})^2$, where $f_{a\pi}$ is the amplitude of the axion–pion transition for the standard axion, $f_{a\pi} = 2 \cdot 10^{-4}$ [11]. Therefore²

$$\sigma(X_a + Pb \rightarrow h) \approx A f_{a\pi}^2 (v/f_{pq})^2 \sigma_{\pi n} \approx 5 \cdot 10^{-34} \text{ cm}^2. \quad (19)$$

With this cross section on the path of lead of 100 m one event (3), (18) per hour will be observed. The increase of additional $U(1)$ symmetry scale to one order gives the decrease of the events number in lead of four orders, because we really think it is possible to reach $f_{pq} \sim 10 \text{ TeV}$ in this experiment.

The background for the reaction (3), (18) will be produced via the high energy photon interaction with the matter of detector. With good wall behind vacuum camera our lead detector can destinate only neutrinos produced in this wall. Their angular spread ($> 300 \text{ MeV}/E$) is much higher that of LGP's calculated above. Besides, energies of these neutrino should be less than the energies of LGP's.

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²The cross-section of lepton pairs production in Bete-Haitler reaction $X + Pb \rightarrow e^+e^- + \dots$, $X + Pb \rightarrow \mu^+\mu^- + \dots$ is approximately an order less then cross-section discussed.

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